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Reduced DOF Type Walking Robot Based on Closed Link Mechanism

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1. Introduction

The types of mobile robot can be roughly divided into three categories, wheeled type, crawler type and legged type. In these types, walking machine (legged type robot) has some of noteworthy strong points that other types of mobile robot don't have. Especially, high adaptability to the terrain is one of the most important strong points of walking machine. The fact that general type of walking machine has many numbers of DOF is essential reason of the above mentioned strong point. However, this fact causes a serious problem that it is very difficult to build up a walking machine that can be into practical use. The following matters are the main reason that disturbs to make walking machine into practical use.

1. Automatic control is required for each DOF (Degrees Of Freedom)
2. Energy cost of walking machine is fully worse than that of other kinds of mobile machines

It goes without saying that automobile that is typical type of wheeled machines has been already made into practical use. In case of automobile, its essential DOF is only two. Therefore, it is able to put the DOF of them under human control. On the contrary, in case of walking machine, number of DOF is too many to put them under human control. Thus, technique of automatic control including complex calculation of kinematics is absolutely required for walking machine.

The second matter is more serious. The fact that walking machine requires many DOF means that many actuators corresponding to the number of DOF are required. Although increasing of number of actuators does not always influenced to efficiency of energy cost, it is very difficult to realize mechanical design that can keep superior energy efficiency. As a result of it, energy costs of walking machine is often made be so bad. Some design technique is required to solve this problem.

To overcome the problem, a new notion that is called reduced DOF design has been proposed. Generally, conventional walking robot requires three DOF for each leg. Therefore, 12 DOF and 18 DOF are required for general type of quadruped machine and that of hexapod machine for each. However, these numbers are not always minimum required number for walking machine. On this point of view, to improve energy efficiency of walking machine by reducing number of DOF is main purpose of the notion of reduced DOF. Based of this notion, some types of walking robot has been developed (Yoneda et al. 2001), (Ota et al. 2001), (Iida 2003) and (Behzadipour 2004).

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In this chapter, we propose a new type of walking machine in that the reduced DOF design is applied. When the notion is applied, we need to pay enough attention to the following matter. It has no meaning, if merit of walking machine is completely lost by reducing DOF. As mentioned before, the strong point of walking robot is its high adaptability to the terrain. Therefore, we have considered a walking environment that includes combination of flat terrain and some steps such as a stair. We can often find such environment, because usual environment designed for human walking satisfies such condition. Typical example of such environment is office and factory.

In the first part of this chapter, we describe basic design of reduced DOF walking machine. In other words, legs and joints arrangement are discussed. In the next section, suitable gait for our walking machine is considered, and inverse kinematics is solved. Some results of simulation are shown in the next section. In the final section, strategy for walking over a step is explained. As a result of our design under the condition, we have got the following conclusion. For step over obstacle, minimum required number of DOF is 7, and maximum is 9. If walking environment is only limited to flat terrain, required number of DOF is only 6.

2. Design joints arrangement and leg mechanism

Except for the notion of reduced DOF, some mechanical design techniques that improve energy efficiency of walking machine have been proposed. GDA (Gravitationally Decoupled Actuation) and MDA (Motion Decoupled Actuation) are the most famous of the techniques. The GDA is a concept to avoid energy loss that is generated by interference of actuations (Hirose 1984). Then, the notion of the MDA is to make a purpose of actuation clear (Koyachi et al. 1991).

At the first step of joint arrangement design, we have considered these two concepts. However, one of the methods to realize these notions is the same method that is to decouple actuation of walking machine into vertical direction and horizontal direction. By using this method, we can list the required function for each direction as follows.

1. Actuation for horizontal direction should be used for propelling the body.
2. Actuation for vertical direction should be use for changing standing phase and swing phase and for adaptive motion to the terrain.

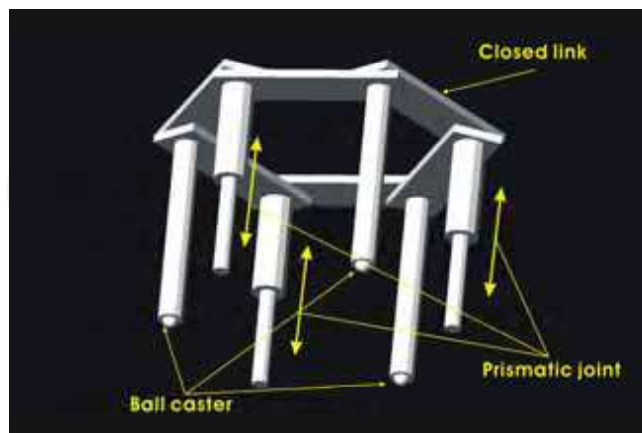


Figure 1. Joint configuration of reduced DOF robot

Figure 1 shows joint configuration of our robot based on these results. This walking machine has six legs along vertical direction. Although three of six legs have active joint that makes prismatic motion into vertical direction, the remaining three legs has no active joint. While they have no joint, they have a ball caster in the sole of leg. This means that these legs make swing phase with keeping contact to the ground.

Then, the six vertical legs are connected by a hexagonal closed link that has six joints. Function of the links is not only to connect the vertical legs, but also to make horizontal motion of robot. Three joints of six joints are active joints and the other joints are passive joints. These numbers are just enough to decide shape of closed link. In the closed link, active joints and passive joints are placed alternatively. Then, vertical legs which have ball caster are placed under the passive joints, and vertical legs without ball caster are placed under the active joints.

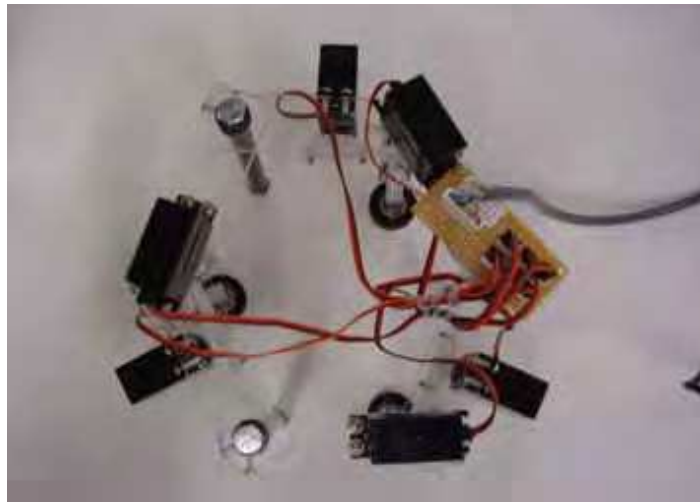


Figure 2. Overview of reduced DOF walking robot (Top view)

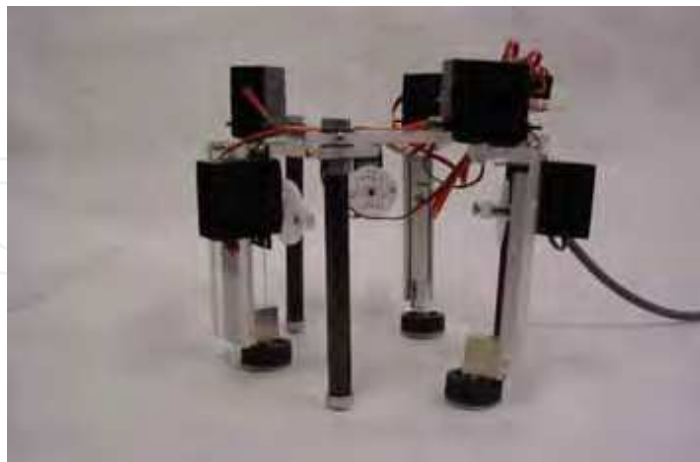


Figure.3. Overview of reduced DOF walking robot (Side view)

By use of the mentioned design, we have developed a walking robot as show in Figure 2 and Figure 3. Since this is a prototype model to confirm basic gait to apply the robot, all actuators is driven by RC-servo. For vertical prismatic joints, simple linkage mechanism is applied to transform rotational motion to prismatic motion. Length of the link in the closed link is 150 [mm] and the height of vertical leg is 120 [mm].

3. Planning of suitable gait

3.1 Basic walking manner

In our mechanism, it is impossible to apply conventional gait for general type of multi-legged walking robot. We need to develop new gait suitable for our robot. Here, to discuss our gait, we define some terminology that is available in this study.

H-leg (Holding leg) : A leg that has no ball caster in the sole. In other words, a leg that holds the ground well, when the leg in the standing phase.

S-leg (Slippery leg) : A leg that has a ball caster in the sole. In other words, a leg that can move even if the sole contacts to the ground.

semi-standing phase : A moment or state that S-Leg is relatively stopping on the ground.

semi-swing phase : A moment or state that S-Leg is relatively moving on the ground.

Basic gait of our robot is realized by a simple motion that one of three H-legs should make swing phase one by one and moves to the next contact point to the ground. The shape of the body is transformed by repetition of the simple motion, and the body is propelled. Here, we should pay attention that the closed link corresponds to the body in our robot.

In case of general walking robot, standing legs must be moved backward relative to the body. This means that it is required to build up a trajectory for standing legs. However, we don't need to pay attention to the motion of standing legs. This is one of the features of our robot.

Then, we explain motion sequence of each leg based on Figure 4. In this figure, *H-legs* are named as H_i ($i=1, 2, 3$) and *S-legs* are name as S_i ($i=1, 2, 3$). Then, active joints in the closed link are named as J_{ai} ($i=1, 2, 3$) and passive joints are named as J_{pi} ($i=1, 2, 3$). Note that the positions of H_i and J_{ai} is the same position in case of top view. Similarly, S_i and J_{pi} is the same position. Since *H-legs* and *S-legs* are placed alternatively, position of the remaining *H-legs* that are in standing phase is fixed to the constant point during one of three *H-legs* is in the swing phase. In Figure 4, it is assumed that leg H_2 and leg H_3 are in the standing phase and leg H_1 is in the swing phase. In this case, the position of leg H_1 can be decided by angles of three active joints J_{a1} , J_{a2} and J_{a3} . If position of H_1 is moved, positions of S_1 and S_3 is moved automatically. This means S_1 and S_3 is in semi-swing phase. On the other hand, since the position of S_2 between H_2 and H_3 is fixed, S_2 is in semi-standing phase.

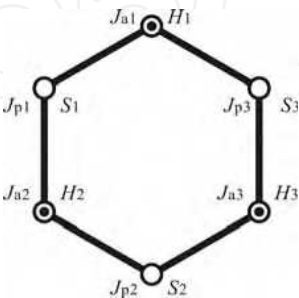


Figure 4. Definition of legs (Top view)

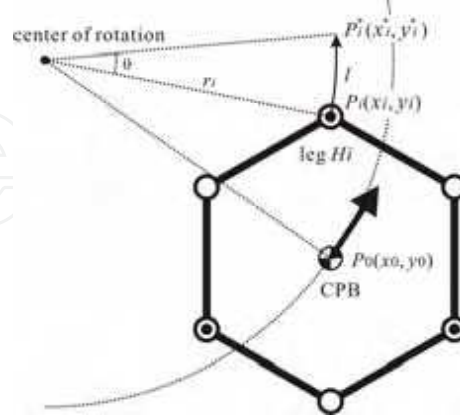


Figure 5. Coordinate system for rotational walk

3.2 Consideration of contact point

In this section, we think about suitable contact point for each leg to realize suitable gait that corresponds to walking speed. First of all, we calculate contact points when robot makes rotation around a centre position. This calculation can also treat straight walking by set the centre position far away. On the contrary, if centre position is inside of the body, turning on the spot can be performed. Figure 5 is coordinate system to seek contact point to realize the rotation. Since motion of our robot is decoupled to horizontal and vertical direction, it is not required to think about vertical component. Thus, point of discussion can be narrowed into horizontal plane. In this figure, the centre position of rotation is P_0 , and P_h is position of a leg in swing phase. The target of the contact point can be calculated by the following equation.

$$x_i^* = r_i \cos(\theta + \phi) + x_0 \quad (1)$$

$$y_i^* = r_i \sin(\theta + \phi) + y_0 \quad (2)$$

Where,

$$\phi = \arctan 2(y_i - y_0, x_i - x_0) \quad (3)$$

$$r_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2} \quad (4)$$

Here, meanings of the other parameters are as follows.

x_i, y_i : Position of leg i
 x_0, y_0 : Centre position of rotation

In equation (1) and (2), θ means an angle of rotation in a step. Actually, it is not suitable to decide θ directly. θ should be considered with stroke length l by using the following equation.

$$\theta = \frac{l}{r_i} \quad (5)$$

We can decide the stroke length l based on the workspace of the robot.

3.3 Inverse kinematics to decide the contact point

We will now discuss inverse kinematics to get to the contact point. The most troublesome problem is closed link mechanism corresponding to the body of our robot, and shape of the body is transformable. In other words, it is difficult to define body coordinate system for our robot. For this reason, we narrow the problem to the above mentioned situation, that positions of successive three legs (two *H-legs* and one *S-leg*) are fixed. For example, if leg H_1 in Figure 4 is in swing phase, the positions H_2 , H_3 and S_2 are fixed. This means that we can treat this problem as four link kinematics problem. Then, we have defined body coordinate system as follows. (See Figure 6)

1. The origin is placed at the one of the *H-legs* that are in standing phase.
 2. X-axis goes through both of the *H-legs* that are in standing phase.
- Based on the definition, inverse kinematics can be calculated by the following equations.

$$\theta_1 = \arctan 2(y, x) - \arctan 2(\sin \theta_2, 1 + \cos \theta_2) \quad (6)$$

$$\theta_5 = \arctan 2(y, x + d) - \arctan 2(\sin \theta_4, 1 + \cos \theta_4) \quad (7)$$

$$\theta_3 = 2\pi + \theta_1 + \theta_2 - \theta_4 - \theta_5 \quad (8)$$

Where,

$$\theta_2 = \cos^{-1} \frac{x^2 + y^2}{2l^2} \quad (9)$$

$$\theta_4 = \cos^{-1} \frac{(x + d)^2 + y^2}{2l^2} \quad (10)$$

x, y : Position of target
 l : Length of a link

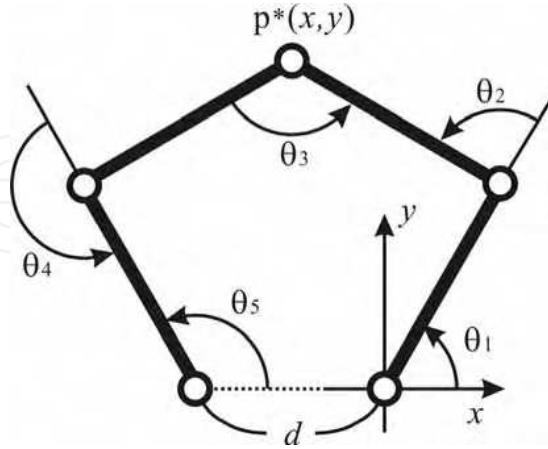


Figure 6. Local coordinate system for inverse kinematics

4. Evaluation of static stability

In case of general type of walking robot, walking motion consists of so many kinds of parameters. Thus, since there are infinite kinds of gaits, it is extremely difficult to seek optimally stable gait by analytical method. In the field of multi-legged walking, it is well known that wave gait is optimally stable gait. But, this fact is found from observation of animal's walking and insect's walking. On the other hands, it is impossible to find suitable gait for our robot from observation, because similar kind of animal or insect does not exist. However, since sequence of our gait is very simple and kinds of parameter are very limited, kinds of gait are very limited. Thus, it is possible to search suitable gait by computer calculation for all possible gaits. Since the number of legs that can be in swing phase at the same time is only one, order of swing leg is only one factor. Additionally, the combination of the order is only three. Therefore, we have calculated static stability by computer simulation for all three gaits. As criterion of static stability, we have used longitudinal stability margin. The result will be shown in next section.

5. Simulation and experiments

Based on the above mentioned strategy, we have performed some simulations and experiments. First, we examined longitudinal stability margin for the three gaits for case of straight walking. Figure 7 shows the result of the simulation. Since our robot can walk straight to any direction, we checked stability for all directions. Therefore, horizontal axis in Figure 7 means walking direction. As the result, three gaits traces similar result. Then, Figure 8 shows locus of CPB (Centre Point of the Body) in case of circular walking with $R=0.5[m]$. Since figure of the robot's body is transformable, it is difficult to define centre point of the body. In our study, we defined CPB that is centre of gravity of a triangle that is made by points of three H-legs. Therefore, the CPB does not completely trace circular trajectory.

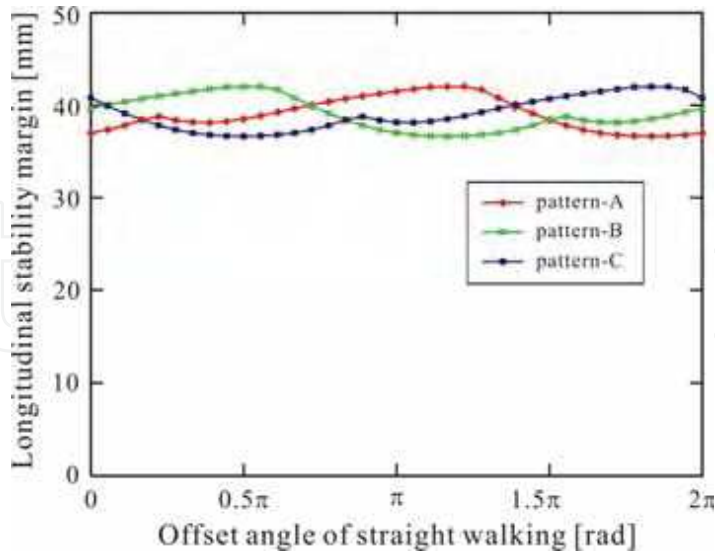


Figure 7. Result of longitudinal stability margin

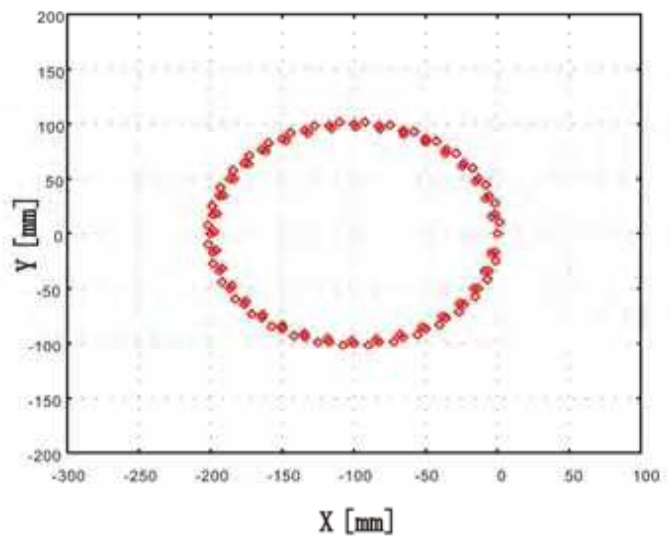


Figure 8. Result of CPB in circular walk

Figure 9 shows locus of CPB in case of turning on the spot. The CPB does not fixed the same point due to the same reason as the last one. However, the difference is very small in comparison with the size of the body. These simulation results are confirmed as a result of experiment by use of our robot. As result of that, we can get the same result to the simulation.

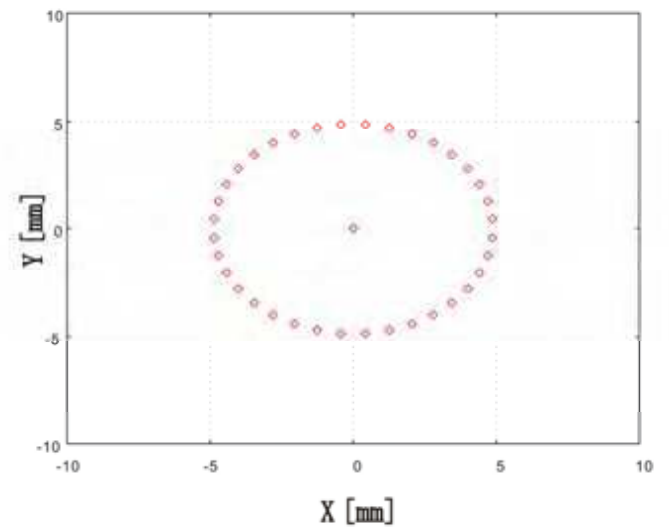


Figure 9. Result of CPB in turning on the spot

6. Sequence for walking over a step

The final point that we should discuss is sequence for walking over a step. It is impossible to walk over a step by using above mentioned configuration that has only six active joints. However, if one of the *S-legs* gets additional active joint that makes prismatic motion to the vertical direction, it can walk over a step by using the following sequence. The sequence is explained based on a case shown in Figure 10. Here, we assume that leg S_2 gets additional vertical joint. The sequence can be explained as the following descriptions.

1. Leg S_2 must be at the tail of the robot. In other words, leg H_1 must be at the head of the body. (Step 01 to 04)
2. Lift up leg H_1 to upper side level, and put it on the upper level. (Step 05 to 10)
3. The height of the body should be lifted up to the upper level. Here, leg S_2 must keep contact to the lower ground. Therefore, length of the leg S_2 must be extended by using additional joint. (Step 11))
4. Put legs S_1 and S_3 on upper floor respectively. (Step 12 to 23)
5. Put legs H_2 and H_3 on upper floor respectively. (Step 24 to 29))
6. Put leg S_1 on upper floor. (Step 30 to 36))

In this sequence, required additional joint for *S-leg* is only one. However, it is not useful, because the direction of the body is limited when robot goes in to a step. If remaining two *S-legs* have additional vertical joint for each, it is easy to access to steps.

7. Conclusion

In this chapter, we have proposed a new type of walking machine by use of reduced DOF mechanical design. Our walking machine is designed for environment that has combination of flat terrain and some steps. This mobile environment is often found in environment for human walking, such as office or factory. Therefore, our walking machine is enough practical, though it has a limitation in walking environment.

As the result of our simulations and experiment, we can get the following results. Our walking machine can walk on flat terrain by use of 6 DOF. Then, to realize walking over a step, 7 DOF is minimum required number of DOF. In this case, there exists a limitation about the body direction. If more than 2 DOF are applied, it can remove this limitation. As mentioned above, general hexapod walking machine requires 18 DOF totally. Thus, our robot can reduce number of DOF less than or equal to the half number of general type.

Our walking machine has several strong points as well as the reduced DOF design. One of them is that the machine can keep high static stability, because more than five legs including the *S-legs* always keep contact to the ground. Then, the combination of the vertical prismatic joints and closed linkage of the body can realize high mechanical stiffness.

Although we can confirm the validity of our walking machine by use of prototype model, we need to solve the following problems to make the machine into practical use. In the bottom of the *S-legs*, ball caster is applied. In case of prototype model, it does not cause mechanical problem, because size of the model is very small. Some redesign is required for this part, when we build up a practical size of the walking machine. One more problem is about the body shape. The main body of our machine is based on the hexagonal closed link mechanism. Therefore, this link mechanism is not suitable for carrying load, since the shape of the body is always changeable. Some device may be required for such purpose.

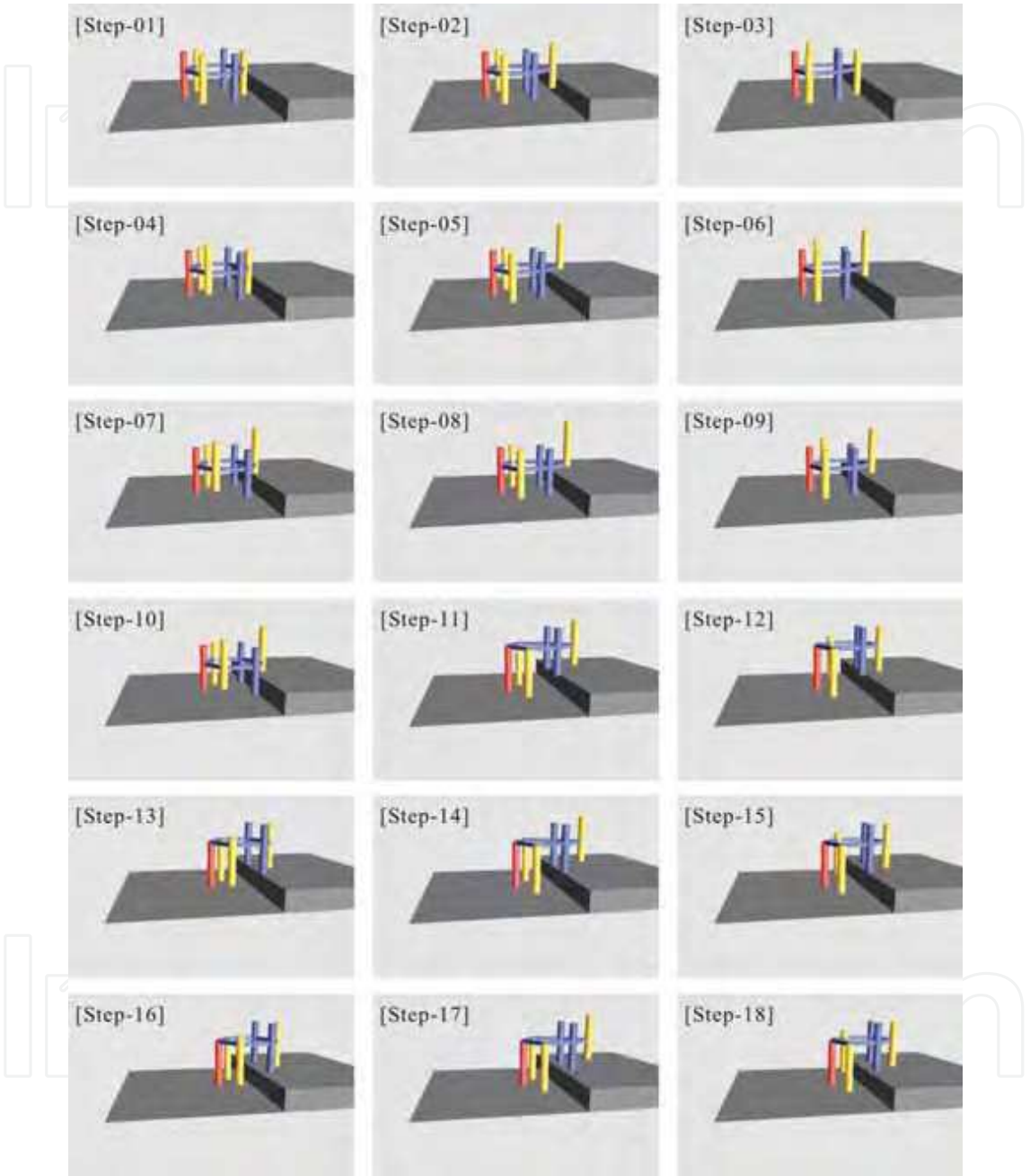


Figure 10(a). Sequence for walk over a step (from Step 1 to 18)

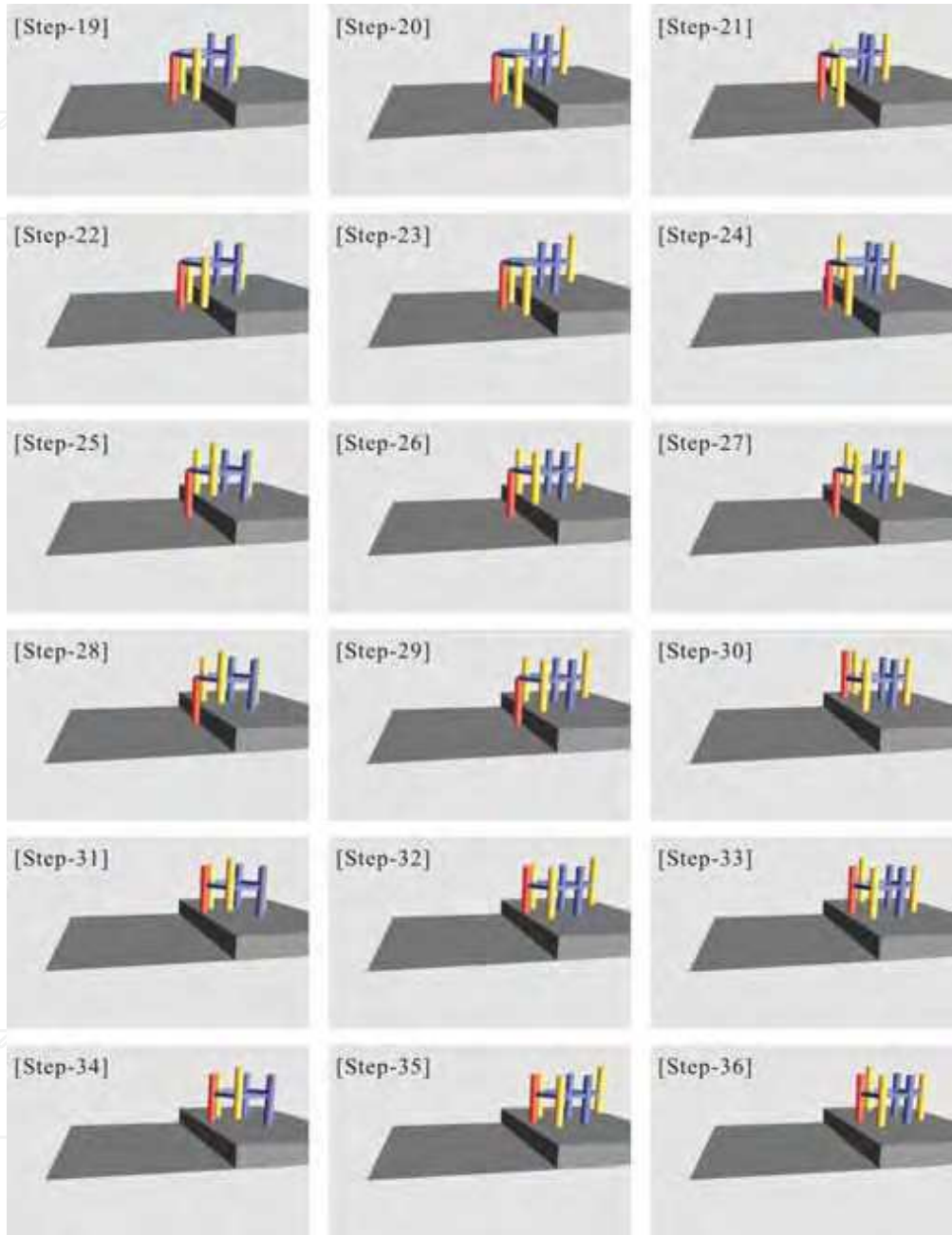


Figure 10(b). Sequence for walk over a step (Continued, from Step 19 to 36)

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.

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